Renewable and Sustainable Energy Reviews 13 (2009) 2661–2667

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of brackish water reverse osmosis (BWRO) system designs

M.A. Alghoul *, P. Poovanaesvaran, K. Sopian, M.Y. Sulaiman

Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia

ARTICLE INFO

Article history:
Received 24 October 2008
Received in revised form 23 February 2009
Accepted 25 March 2009

Keywords:
Brackish water
Reverse osmosis
Water desalination system
BWRO system

ABSTRACT

Brackish water are any water sources with TDS between 1000 and 15 000 mg/L. Brackish water cannot be consumed by us directly due to its high salinity. According to World Health Organization (WHO), water with salinity below 500 mg/L is acceptable as drinking water. There are quite a large number of research that had been done on BWRO. Each of them has agreed with a common design on optimum BWRO design with a slight modification in order to improve more and make a better BWRO system. BWRO systems which have been tested in real situation agree that the single stage system with module connected to reject water is the most optimum system both economically and environmentally. There is some improvement done to the design by using SWRO membrane at the second stage. This improvement increases recovery rate to about 83% and reduces boron concentration at the same time. Another design is by using hybrid combination of ultra-low and conventional RO membranes. Hybrid improves permeate quality. It is also possible to create a hybrid array by mixing membrane element types within a pressure vessel itself. Co-operating an efficient module arrangement into a complete BWRO system will reduce energy consumption. Energy-recovery device is a component that must be included in any small or large-scale systems. A small-scale RO system, without energy recovery, would typically consume two to three times more energy. This will be more for large-scale systems. While single stage system with module connected to reject water is preferred by researchers who have done real environment testing, simulation prefers to add another membrane to the reject water of the second module. This system is yet to be tested in real environment to prove its standing.

Contents

1. Introduction

Water is the most important resource for all living creatures on Earth to survive. Water is abundant on Earth. About 94% are as seawater in oceans while the remaining 6% are fresh water. Out of the total fresh water, about 72% is found in underground and the remainder 27% are as glaciers.

Water can be categorised according to its salinity level. Three main categories of salinity are seawater which has total dissolved solids (TDS) concentration of about 35 000 mg/L or more, brackish water or medium-salinity water with TDS concentration of 1000–15 000 mg/L and fresh water with concentration below 500 mg/L also known as low-salinity water. El-Manharawy et al. [1] discussed in detail the water types.

Brackish water can be further broken down into medium-salinity water with TDS up to 5000 mg/L, medium-salinity water with high natural organic matter (NOM) and TDS up to 5000 mg/L, medium-salinity tertiary effluent with high total organic carbon (TOC), biological oxygen demand (BOD) and TDS up to 5000 mg/L.

Brackish water cannot be consumed directly due to its high salinity. According to World Health Organization (WHO), water

* Corresponding author. Tel.: +60 192510835; fax: +60 389214593.
E-mail address: dr.alghoul@gmail.com (M.A. Alghoul).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.03.013

with salinity below 500 mg/L is acceptable as drinking water. Thus brackish water must be desalinated before it can be consumed by community. Desalination of water is essential to the development and growth of many countries in the world.

Although RO would able to produce water salinity below 500 mg/L, the reject water being produced is with very high salinity and a proper way of disposal is needed or it will effect the ecosystem of surrounds. Hasnain and Alajlan [2] proposed a solution to overcome this problem.

Water scarcity is a problem in remote locations. BWRO provides solution for them by producing fresh water so they would enjoy better living standards. The problem is energy. Bouguecha et al. [3] evaluated the performances of a desalination family prototype in perspective of optimizing its operation as a function of energy availability. The authors have also confirmed the contribution of the storage dissipation system when using solar energy for water desalination, and the advantages brought by the use of this system in terms of a continuous operating mode by excluding the effects of source fluctuations.

BWRO system can be designed in a wide way from the number of membranes in a module and the arrangement of membrane module. Vince et al. [4] discussed about the number of membranes in a module. The author has shown that using seven membranes for both first and second stages will have a recovery rate of 82%, with a recovery rate of 64% for the first stage and a recovery rate of 50% for the second stage.

Lu et al. [5], on the other hand, have simulated membrane arrangement in order to find out optimum module arrangement of RO under different feed concentrations using mixed-integer nonlinear programming (MINLP). In this study, optimal arrangement of the RO modules, pumps, energy-recovery devices, the optimal operating conditions, and the optimal selection of types and number of membrane elements are presented.

Almulla et al. [6] used a different idea to increase water recovery. The author designed a two-stage membrane by using BWRO membrane for the first stage and seawater reverse osmosis (SWRO) membrane at the second stage. The recovery rate using this design is about 83%. The objective of this study was to develop a BWRO system with a good recovery rate and this can be achieved by utilizing SWRO membrane. There are no operation changes in using SWRO membrane as part of BWRO system.

Nemeth [7] provides insights into optimizing performance of ultra-low pressure RO membranes in an innovative system design. The author proposed utilizing hybrid combination of ultra-low and conventional RO membranes. Additional changes are incorporating inter-stage pressure boosting and utilizing permeates throttling at the first stage.

Some brackish water source contains high level of boron concentration. Glueckstern and Priel [8] proposed an alternative boron concentration reduction method in brackish water desalination by using SWRO membrane. The method discussed in this paper can be used with or without complementary boron reduction by selective IX resins but its much more economic. Almulla et al. [6], pointed out that using SWRO membrane on the BWRO system also increases the overall plant recovery.

Weiner et al. [9] explore operating solar and wind powered BWRO system. In this study, the author keeps track of various system components operation, reliability, accuracy and adaptability. Another study was done by Joyce et al. [10] on small reverse osmosis units using PV systems in rural places. Joyce et al. also showed support for the usage of alternative energy, PV to power BWRO system as its consumption of energy is very low.

Cost is one of the most important criteria that is calculated before building a BWRO system. Gocht et al. [11] investigated the technical feasibility and cost benefit analysis of a PV-powered brackish water small-scale desalination plant in a rural area.

2. Reverse osmosis

Desalination is a water treatment process that removes salts or other dissolved minerals and contaminants such as dissolved metals, radionuclides, bacterial and organic matter from high salinity water to produce fresh water. Desalination is used to improve the quality of hard waters (high in concentrations of magnesium and calcium), brackish waters (moderate levels of salt) or seawater. Desalination processes involve saline feed water (brine), low-salinity product water (fresh water) and very saline concentrate (reject water). Saline feed water (water before the desalination process) will be separated into two products: fresh water and water with high concentration of salts or brine, after it goes through the desalination process.

The most widely used technologies for desalination are thermal processes and membrane processes. Reverse osmosis falls under the membrane process category. Osmosis refers to the net movement of water from an area of lower concentration to an area of higher concentration across a partially permeable membrane. If excess pressure is applied on the higher concentration, we could reverse the process. This process is known as reverse osmosis (RO). Water would move from an area of higher concentration to an area of lower concentration. The saline feed water is pumped into a closed vessel where it is pressurized against the membrane. The water molecule would pass through the membrane increasing the concentration of the reject water producing purified water on the other side. Most of the energy is used for the initial pressurization of the feed water. Initial pressurization for brackish water ranges from 250 to 400 psi [12,13].

As fresh water permeates across the membrane, the feed water becomes more and more concentrated. Brackish or seawater at a high pressure, greater than the osmotic pressure is fed through the membrane. There is a limit to the amount of freshwater that can be recovered from the feed without causing fouling of the membranes. Brackish water RO plants have recovery rates as high as 90%. The RO system major components include membrane modules, high-pressure pumps, power plant, and energy-recovery devices as needed [12].

Two major factors controlling the energy requirement of an RO system are membrane properties and salinity of the feed water [13]. Higher water salinity requires more energy to overcome the osmotic pressure, where the RO system needs only mechanical power to raise the pressure of feed water.

Water desalination by the technique of reverse osmosis has proved to be the lowest energy consuming technique compared to other desalination processes according to many studies [3]. It consumes about half of the energy needed for thermal processes. Also, the modularity of reverse osmosis units, their simplicity of operation, their compact sizes and lower environmental impacts give them priority to be used for water desalination in remote areas [14]. Other advantages of RO systems include low investment costs at low capacities, ease of operation, flexibility in capacity expansion, operation at ambient temperature and short construction periods.

RO is very flexible in the water quantity and quality, the site location and the start-up and shut-off [15]. In addition, RO plants are constructed in a modular way and can be well adapted to a renewable energy supply. Factors such as the daily per capita consumption, the total population as well as the hours of operation of the unit per day are critical factors for the sizing of the RO unit.

3. *Water type*

The main goal in the design of a BWRO system is to achieve the required water salinity with the lowest cost. The cost of water produced by desalination processes depends on [16]:

(a) the total capital investment of the system (RO, battery, pumps, concentrate disposal, storage tanks)
(b) the cost of operating, maintenance and repair of the system.

Parameters which are important in designing a BWRO system are feed source, feed concentration, feed flow, product flow, and product quality. A good BWRO system would try to minimize feed pressure, number of membranes used but maximize permeate quality and recovery. With a low feed pressure, the life span of the membrane could be increased but it would compromise recovery ratio.

Brackish water composition varies widely, therefore the composition of it must be known before any design can be done [1]. A complete and accurate water analysis must be obtained. Water composition need to be analysed. An example of brackish water composition is shown in Table 1 [17]

Another important parameter is the temperature. Temperature variation for the brackish water must be measured also. Temperature variation can impact the scaling potential in a BWRO system. This is very obvious especially when silica and bicarbonate level in the feed water is high.

Membrane fouling is due to particles and colloidal material which are present in the feed water and are concentrated on the membrane surface. The Silt Density Index (SDI) and the permeate flux is the main reason for fouling to occur in membrane. A BWRO system must operate within a frame of operating conditions to minimize the fouling rate. Organic matter, inorganic salt precipitation, colloidal or particulate deposits and in the longer term by microorganism growing in the system and on the membranes cause fouling in a RO system [17,18]. The scaling substances are Ca, Mg and the anions of SO_4 and HCO_3. These substances exist in relatively high concentrations and the calculated total hardness is in the range of 1500–3000 mg/L as $CaCO_3$. The Fe concentration is 5–15 mg/L. As for SiO_3, which is a fouling substance for membranes, its concentration is in the range of 10–20 mg/L [13].

4. A complete brackish water reverse osmosis (BWRO) system

The design for the most optimum combination of component starts by measuring input and output efficiency for each component that made up RO system. Basic components to make an RO system are:

- Pre-treatment
- High-pressure pump
- Membrane module
- Post-treatment

Table 1
Example of brackish water composition.

Parameter	Unit	Sample value
Arsenic (As)	mg/L	<0.005
Boron (B)	mg/L	0.21
Calcium (Ca)	mg/L	142.1
Chloride (Cl)	mg/L	1483
Fluoride (F)	mg/L	<0.10
Iron (Fe)	mg/L	28.87
Magnesium (Mg)	mg/L	192
Manganese (Mn)	mg/L	0.5
Nitrate (NO^{-3})	mg/L	<1.0
Nitrite (NO^{-2})	mg/L	<0.1
Potassium (K)	mg/L	19.2
Sodium (Na)	mg/L	1125
Sulphate ($SO_4{}^{2-}$)	mg/L	340
Total hardness ($CaCO_3$)	mg/L	1146
pH	–	6.7
Conductivity	mS/cm	6.35
Turbidity	NTU	370

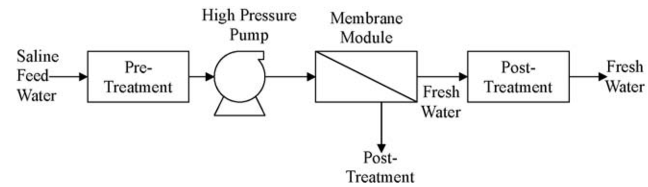

Fig. 1. Basic components of reverse osmosis plant.

These components are arranged as shown in Fig. 1, which shows the flow of saline feed water till it is changed to fresh water discharging concentrated saline water. This is the most basic BWRO system.

Pre-treatment is the first process of the saline feed water. Pre-treatment varies depending on location source of feed water. Pre-treatment often includes the addition of chemicals to the feed water that control fouling and scaling of the membranes. Feed water is introduced at a first pressure level and pre-treated to remove suspended solids. This would increase the lifespan of the membrane. Two stages of pre-treatment are filtration and addition of chemical. Filtration would protect membrane from large debris while addition of chemical would control biological and organic fouling.

High-pressure pump is needed to increase the feed water to a much higher pressure than the first before pre-treated feed water moves into the membrane module. High pressure is needed to enable reverse osmosis in the membrane module where feed water is pressurized against the membrane allowing fresh water through and reject concentrated discharge. After passing through the membrane module, fresh water flows into post-treatment while concentrated saline water is discharged.

Fresh water from the membrane module is not yet safe to be consumed. After passing through membrane module, fresh water needs to be stabilised before it is ready to be consumed. In post-treatment, hydrogen sulfide is removed and pH of fresh water is adjusted.

The reject water needs to be processed before being released into environment. Reject water which is high salinity would damage the ecosystem of its surroundings, especially for brackish water where there is no option to dilute the reject water before disposing. Hasnain et al. [2] proposed a solution to overcome this problem. In the paper, a simple, cheap yet effective design was proposed by using solar stills. This design can be applied for any location with enough sunlight.

Weiner et al. [9] explores operating solar and wind powered BWRO system. It is possible to operate BWRO system with alternative energy source as it consumes very less energy

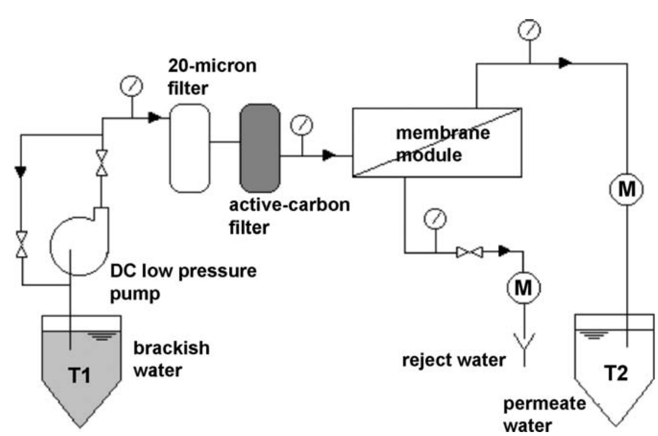

Fig. 2. Schematic configuration of small RO experimental pilot plant.

Table 2
Overview of existing PV-powered RO system designed to treat brackish water.

Location	TDS (g/L)	Pressure (bar)	Salt retention (%)	Recovery (%)	Clean water (m^3/d)	Power array (kW)	Battery	SEC (kWh/m^3)
Portugal	Conductivity 2–5 mS/cm	4	90	2	0.02	0.15	No	25.6
Australia	5	–	–	16 or 25	0.4	0.12	No	–
Australia	3.5	10–4	92	10	0.1	0.26	No	8
Mexico	1.5–5	40	–	–	0.7–1.4	2.5	Yes	4.0–6.9
Oman	1	12	96.6	65–70	5	3.25	Yes	2.3
Israel	4	14–16	98	50	3	3.5	Yes	–

compared to other water desalination methods. In this study, the author keeps track of various system components operation, reliability, accuracy and adaptability.

Joyce et al. [10] worked on small reverse osmosis units using PV systems in rural places. In the study, the author concluded that for the small RO system the energy consumption decreases as feed water recovery and feed pressure increase. The design is shown in Fig. 2, uses filters, pumps and membrane to put together this system will the most effective in power consumption which reduces the cost.

While quite a number of reverse osmosis units driven by renewable energy have been developed for seawater desalination, only few PV-powered RO have been designed to treat brackish water [17]. Table 2 shows overview of existing PV-powered BWRO systems.

Cost is one of the most important criteria that is calculated before building a BWRO system. Gocht et al. [11] investigated the technical feasibility and cost benefit analysis of a PV-powered brackish water small-scale desalination plant in a rural area. This study revealed the socio-economic feasibility for the desalination by means of a transient and discontinuous operated RO directly coupled with a PV system.

5. BWRO module arrangements

5.1. Single stage module systems

Fig. 3 shows feed flow is pumped into the RO module with a designated pressure which will split into product water and reject water. BWRO are highly sensitive to the effect of the concentration polarization at higher pressure, as it is normally operated at a pressure lower than 15 bar [1].

Single stage system with recovery turbine and recycle reject water is shown in Fig. 4. This system is similar to the previous two systems but part of the reject water is connected to the feed water and energy-recovery device (ERD) is added. A system without ERD, would typically consume two to three times more energy. Most of small-scale systems are built without any energy-recovery mechanism; this keeps capital costs down but has a heavy penalty in ongoing energy costs.

Fig. 5 describes single stage system with module connected to reject water. Feed water is split into product water with less pressure and the reject water with pressure near applied pressure since the reject water represents most of the energy applied to the

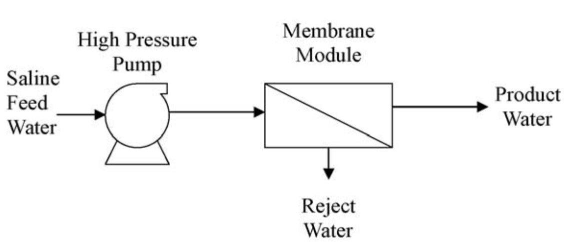

Fig. 3. Single stage reverse osmosis system.

feed pumps. This configuration must be operated above minimum brine or reject flow rate to prevent concentration polarization from occurring.

In the system shown in Fig. 6, feed water salinity of first stage is low which makes it high flux but low pressure. Concentrate from the first stage becomes feed for the second stage. Salinity of second stage feed water will be higher which makes it low flux but high pressure. Therefore, feed pressure must be increased before it enters the second stage. This can be done by installing inter-stage booster pumps [7]. With a booster pump, the feed water pressure

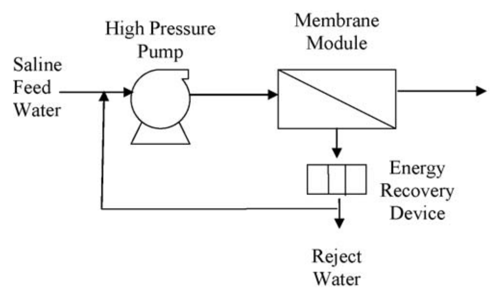

Fig. 4. Single stage system with recovery turbine and recycle reject water.

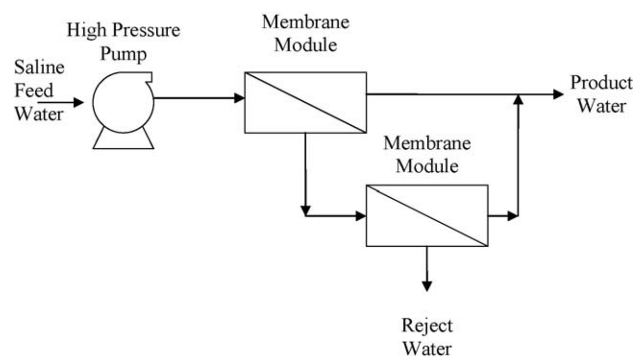

Fig. 5. Single stage system with module connected to reject water.

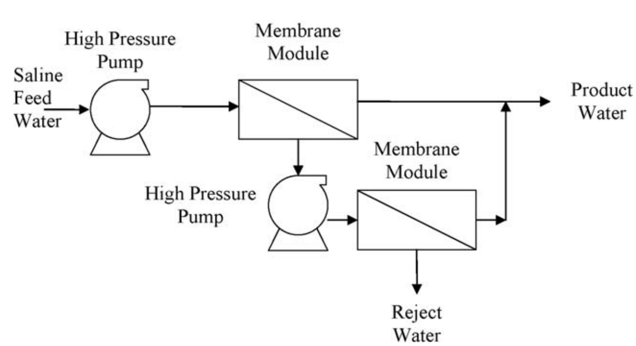

Fig. 6. Single stage system with module connected to reject water with booster pump.

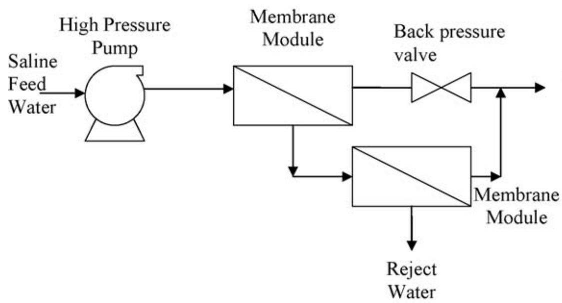

Fig. 7. Single stage system with module connected to reject water with back-pressure valve.

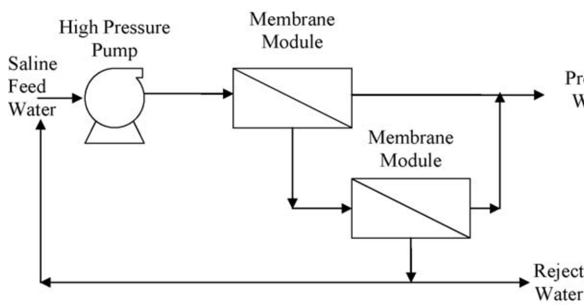

Fig. 8. Single stage system with recycle reject water.

and water flux can be increased to an optimum value and second stage can be operated in nominal hydraulic conditions. Adding a booster pump makes it possible to install smaller membrane area which leads to higher total recovery rate and therefore reducing the electricity consumption and the invest costs [4].

Sometimes this system will be slightly imbalanced; using back-pressure valve is a cost-effective means to equalize the flux between passes. The back-pressure valve is connected after the first stage as shown in Fig. 7 [7]. Another similar system is shown in Fig. 8 which recycles reject water.

Single stage system with multi-membranes with recycle reject is shown in Figs. 9–11. With decreasing feed concentration, the structures employed during the design vary from single stage two to three membranes with brine recycle. This design increases recovery ratio and decreases product cost.

For feed concentration 3000 mg/L, the optimal RO structure is shown in Fig. 9. The brine leaving stage three membrane is partly recycled, while the others come into ERD. A brine recycle around the third membrane that leads to higher overall recovery appears in the optimum structure. Although the brine recycle will increase the feed concentration of the third membrane, the brine concentration coming from the second membrane is relatively lower, and the third membrane can still produce permeate required. The cost for single stage with three membranes is

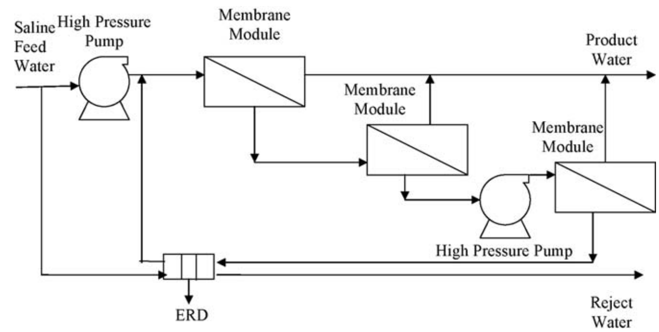

Fig. 10. Optimum RO system for feed concentration 6000 mg/L.

higher than that of the optimal one, but the structure is relatively simple. Therefore, the suboptimum solution may be better for the case from operative point of view [5].

For the system shown in Fig. 10, there is a bypass into the second stage for the brine coming from the first unit of the first membrane for the single stage membrane system, while the others enter the second unit of the first membrane. The brine bypass is useful to dilute the feed stream of the second membrane. As shown in Figs. 10 and 11, the first membrane can be made of more unit blocks in series. The feed pumps between units are omitted. The feed stream of the second membrane could be diluted with the brine bypass stream. With decreasing feed concentration of 6000 mg/L, the bypass disappeared. The feed concentration of the second membrane still meets the requirement although without the bypass stream [5].

5.2. Two-stage module systems

The disadvantage of single stage system is its low water recovery; two stages will increase the permeate quality and recovery. The second stage unit will be used to treat all or part of the permeate from the first stage.

Fig. 12 shows two-stage reverse osmosis system where feed water is pumped from the source by feed water pump and is pressurized by the high-pressure pump into the module. The feed water is split into product water and reject water in the first stage. The product water is pressurized by the second high-pressure pump to be as the feed water for the second stage where it is also split into product water and reject water.

Two-stage system with ERD is similar to two-stage system but with addition of ERD and recycle the reject water. This design is shown in Fig. 13.

Two-stage system with module connected to reject water as shown in Fig. 14 is compound of three modules, one is connected to the product water of first stage and the second module is connected to reject water of the first module. The reject water

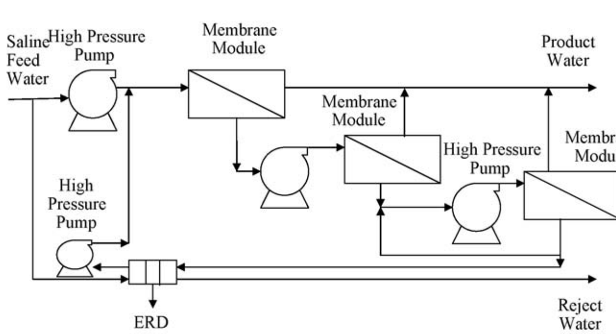

Fig. 9. Optimum RO system for feed concentration 3000 mg/L.

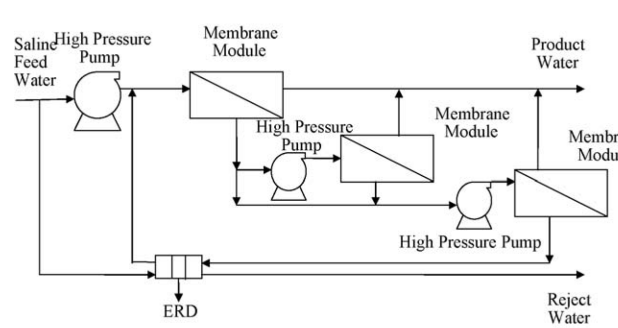

Fig. 11. Optimum RO system for feed concentration 12 000 mg/L.

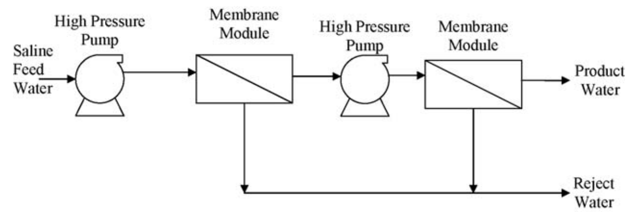

Fig. 12. Two-stage reverse osmosis system.

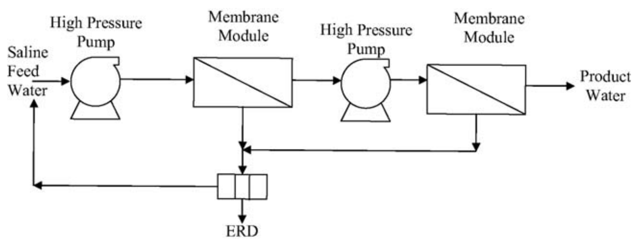

Fig. 13. Two-stage system with recovery turbine and recycle the reject water.

is recycled to be a part of the feed water where the concentration of feed water will increase up to controlled values of concentration of brine in feed and reject water so the feed water from the source when the reject water is recycled is equal to the product water. Another similar system but with recycle of reject water is shown in Fig. 15.

5.3. Optimum BWRO system

Single stage system with module connected to reject water arrangements minimizes electricity consumption which enables the water price to be low. The single stage system with module connected to reject water RO process layout and the water recovery rate are found to be optimal for both economical and environmental objectives. The trade-off between environmental and economical objectives is identified by the definition of the permeate flux. For high permeate flux, low total costs are reached but electricity consumption and desalination environmental impacts are high. Low permeate flux allows to achieve lower electricity consumption but ought to be compensated by larger membrane area and higher costs. A second trade-off is identified between the two main impacts of desalination (electricity consumption and brine discharges). Indeed brine discharge can be reduced only with higher electricity consumption [4].

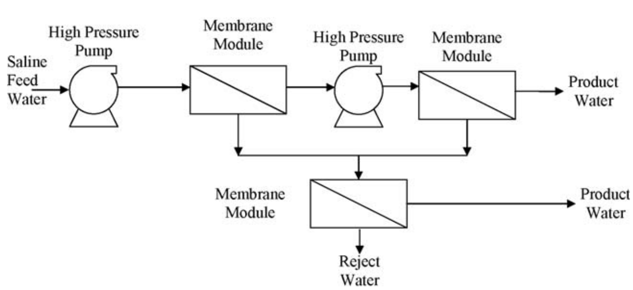

Fig. 14. Two-stage system with module connected to reject water.

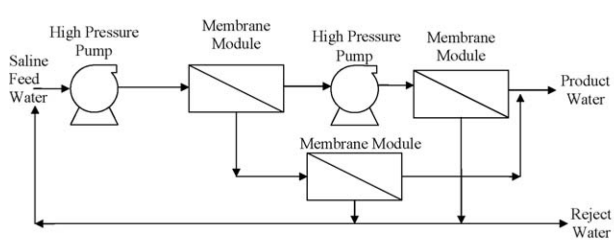

Fig. 15. Two-stage system with module connected to the reject water and recycle the reject water.

Conventional BWRO treatment system is arranged in a staged array where typically the subsequent stage contains half as many membranes as the previous stage (2:1), e.g. 12:6. Vince et al. [4] have shown that using seven membranes for both first and second stage will have a recovery rate of 82%, with a recovery rate of 64% for the first stage and a recovery rate of 50% for the second stage.

Total energy consumption could be lowered more but that would decrease the recovery to 75% however the cost will be more due to increase in total membrane area. Another option is to increase the recovery rates beyond 85% but the cost increases. The optimum recovery rate is about 81% which would cost the least [4].

Almulla et al. [6] designed a single stage system with module connected to reject water membrane with using BWRO membrane for the first stage and seawater reverse osmosis (SWRO) membrane at the second stage. The recovery rate using this design is about 83% which is an increase from 73% with normal membrane. The objective of this study was to develop a BWRO system with a good recovery rate and this can be achieved by utilizing the SWRO membrane. There are no operation changes in using SWRO membrane as part of BWRO system.

Glueckstern and Priel [8] in a different paper showed the advantage of using SWRO membrane as part of BWRO system would able to reduce boron concentration in brackish water and its much more economic method. Boron concentration in the desalination product should be below 0.3 mg/L according to EU. An alternative method for reducing the boron concentration is ion exchanging by boron selective resins and use of special RO membranes developed for the boron removal in low or natural pH. Energy consumption by using this method is very high.

Another innovative way for an optimum performance is provided by Nemeth et al. [10] by using hybrid combination of ultra-low and conventional RO membranes. Hybrid system able to improve permeates quality. According to the author, it is possible to create a hybrid array by mixing membrane element types within a pressure vessel itself.

Single stage system with module connected to reject water with booster pump as proposed by Vince et al. [4] is proved to minimize simultaneously the electricity consumption and cost. The installation of inter-stage booster pumps also appears to be a “win–win” option from an economic and environmental point of view. With a booster pump, the second membrane can be operated in nominal hydraulic conditions, thus leading to a smaller installed membrane area and to a higher total recovery rate, therefore reducing the electricity consumption and the investment costs.

Lu et al. [5] came up with different membrane arrangements for different feed concentrations by using simulation. The author proposed three different designs for BWRO for feed water concentrations of 3000, 6000 and 12 000 mg/L as shown in Figs. 9–11. The unit product cost is proportional to the feed concentration. With increasing raw feed concentration the overall recovery ratio decrease and the product water quality deteriorates. For processing higher feed concentration, the thigh operating pressure is necessary, however, the number of elements and pressure vessels employed in the RO system is less than that of lower feed concentration. It indicated that the arrangement and operation of RO system are more flexible when the operating pressure is relatively lower. When the high operating pressure is necessary, the simple one stage structure is more favored. With

decreasing feed concentration, the structural schemes vary from single to three single stage membrane with brine bypass and recycle.

6. Conclusion

Brackish water composition varies widely depending on the location. The first step before developing a BWRO system is to test the water composition. This step is crucial for the pre-treatment of the BWRO system. Pre-treatment often includes the addition of chemicals to the feed water that control fouling and scaling of the membranes.

There are also other parameters to be considered, the important parameters are feed source, feed concentration, feed flow, product flow, and product quality. An optimum BWRO system would try to minimize feed pressure and number of membranes used but maximize permeate quality and recovery.

There are quite a large number of research that had been done on BWRO. Each of them has agreed with a common design on an optimum BWRO design with a slight modification in order to improve more and make a better BWRO system. Although most of the designs had been tested in the real environment, some is yet to be tested as the design is via simulation.

All the authors who have tested out BWRO system in real environment agreed that single stage system with module connected to reject water is the most optimum both economically and environmentally. Improvement on this system had been done by using SWRO membrane at the second stage. Advantage of this improvement is increment of recovery rate to about 83%. This improvement is also able to reduce boron concentration.

Another improvement for an optimum performance is by using hybrid combination of ultra-low and conventional RO membranes. Hybrid system able to improve permeates quality. It is also possible to create a hybrid array by mixing membrane element types within a pressure vessel itself.

Co-operating an efficient module arrangement into a complete BWRO system will reduce energy consumption. Energy-recovery device is a component that must be included in any small or large-scale systems. A small-scale RO system, without energy recovery, would typically consume two to three times more energy. This will be more on large-scale systems.

While single stage system with module connected to reject water is preferred by researchers who have done real environment testing, simulation prefers to add another membrane to the reject water of the second module. This system is yet to be tested in real environment to prove its standings.

One thing is very clear; water desalination by the technique of reverse osmosis has proved to be the lowest energy consuming technique compared to other desalination processes. It is also very simple to operate with compact size with small environmental impacts. Other advantages of RO systems include low investment costs at low capacities, ease of operation, flexibility in capacity expansion, operation at ambient temperature and short construction periods.

References

[1] El-Manharawy S, Hafez A. Water type and guidelines for RO system design. Desalination 2001;139:97–113.
[2] Hasnain SM, Alajlan SA. Coupling of PV-powered RO brackish water desalination plant with solar stills. Desalination 1998;116:57–64.
[3] Bouguecha S, Hamrouni B, Dhahbi M. Operating analysis of a direct energy coupled desalination family prototype. Desalination 2004;168:95–100.
[4] Vince F, Marechal F, Aoustin E, Breant P. Multi-objective optimization of RO desalination plants. Desalination 2008;222:96–118.
[5] Lu YY, Hu YD, Zhang XL, Wu LY, Liu QZ. Optimum design of reverse osmosis system under different feed concentration and product specification. J Membr Sci 2007;287:219–29.
[6] Almulla A, Eid M, Cote P, Coburn J. Development in high recovery brackish water desalination plants as part of the solution to water quantity problems. Desalination 2002;153:237–43.
[7] Nemeth JE. Innovative system designs to optimize performance of ultra-low pressure reverse osmosis membranes. Desalination 1998;118:63–71.
[8] Glueckstern P, Priel M. Boron removal in brackish water desalination systems. Desalination 2007;205:178–84.
[9] Weiner D, Fisher D, Moses EJ, Katz B, Meron G. Operation experience of a solar- and wind-powered desalination demonstration plant. Desalination 2001;137:7–13.
[10] Joyce A, Loureiro D, Rodrigues C, Castro S. Small reverse osmosis units using PV systems for water purification in rural places. Desalination 2001;137:39–44.
[11] Gocht W, Sommerfeld A, Rautenbach R, Melin TH, Eilers L, Neskakis A, et al. Decentralized desalination of brackish water by a directly coupled reverse-osmosis-photovoltaic-system—a pilot plant study in Jordan. Renewable Energy 1998;14(1–4):287–92.
[12] Abdallah S, Abu-Hilal M, Mohsen MS. Performance of a photovoltaic powered reverse osmosis system under local climatic conditions. Desalination 2005;183:95–104.
[13] Mohsen MS, Jaber JO. A photovoltaic-powered system for water desalination. Desalination 2001;138:129–36.
[14] Ahmad GE, Schmid J. Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems. Energy Convers Manage 2002;43:2641–9.
[15] Herold D, Horstmann V, Neskakis A, Plettner-Marliani J, Piernavieja G, Calero R. Small scale photovoltaic desalination for rural water supply—demonstration plant in Gran Canaria. Renewable Energy 1998;14(1–4):293–8.
[16] Bouguecha S, Hamrouni B, Dhahbi M. Small scale desalination pilots powered by renewable energy sources: case studies. Desalination 2005;183:151–65.
[17] Schafer AI, Richards BS. Testing of a hybrid membrane system for groundwater desalination in an Australian national park. Desalination 2005;183:55–62.
[18] Fritzmann C, Löwenberg J, Melin T. State-of-the-art of reverse osmosis. Desalination 2007;216:1–76.